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A modular model for simulating continuous or event runoff

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ABSTRACT A review of stormwater model arrangements is made. Computer programs able to assemble loosely-connected elements are simplest to use and understand. Arrangement of elements and assembly in parallel or series enables all possible types of models to be accommodated. Hydraulic elements are used for surface runoff visualization and groundwater aquifers are simulated in parallel for continuous or long term simulations.

INTRODUCTION

The accuracy of runoff models can be improved at the expense of more and more data. There are many models available with differing levels of sophistication for such studies. The author contends however the biggest cost of modelling is often in learning the ins and outs of a model, and its principles and limitations. On the lower levels of the learning curve many users may wish to dabble with a model, and at the upper end there are many technical aspects to remember. Time away from the model causes users to forget aspects, and it is the ease of initial or re-access which can inspire confidence in the user and enable the model to be used to its fullest. Various types of models are discussed bearing these points in mind.

Sub catchment arrangement

The interconnection of one sub-catchment or element with another can be done in various ways (Fig. 1):

i) Finite difference grids In the case of a homogeneous type catchment a rectangular grid can be superimposed. Thus flows and water depths are computed at grid point. Either one or two directional flow can be assumed. In general two flow vectors must be assumed. An exception occurs if the flow is in one direction parallel to one of the axes. For most undular topography two-dimensional analysis is necessary.

ii) Finite element The computations can be reduced and size and shape of element varied to suite the topography if a finite element approach is used. In general a two-direction flow pattern must be assumed although if the boundaries of elements are perpendicular to flow, one-directional flow can be assumed.

iii) Modular The simplest and most versatile model is one made up of modules which can be linked up at the ends. Generally the flow is one directional along the axis but two dimensional catchments can be made up of modules in parallel and series, i.e. the orientation of the module is ignored because the directional momentum of the water is not considered. It is the latter configuration on which the model describes here is based.

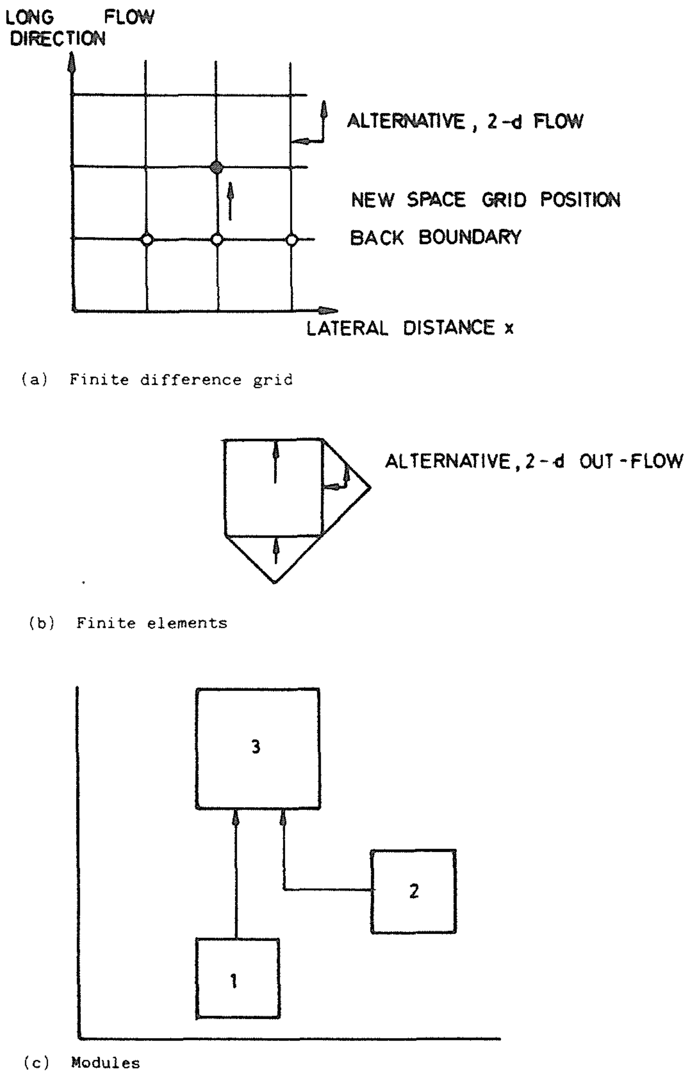

Fig. 1 Alternative grids.

THEORETICAL BASIS

Hydrological models range from statistical to conceptual, embracing probabilistic, curve fitting, black boxes, analogous e.g. cell type (Diskin et al 1984), through to the more hydrodynamically correct. Even the latter range from simplistic e.g. time area (Watson, 1981) though first approximation kinematic type, diffusion equations and hydrodynamic equations (SWMM, Huber et al, 1982). The latter are only necessary for surface runoff simulation and even then are not always warranted. For runoff determination accelerations and backwater effects are not significant. On the other hand the time-area approach which derived from the rational method, does not accommodate the effect of water depth on concentration time. Mono time axes and linear rainfall-runoff relationships have been taken to their extreme in unit hydrograph theory, and as a result the hydraulic basis is often overlooked in sophisticated models e.g. OTTHYMO (Wisner, 1980).

It is into the more hydraulically based models that the majority of research is now directed. By suitable selection of module arrangement, one-dimensional flow can be assumed. i.e. the module axis is taken in the general flow direction. Lateral flow time is neglected, (which could introduce error in flood plane type modules). Transverse i.e. lateral and vertical (for horizontal flow direction) accelerations are also neglected but this is quite satisfactory for all runoff modelling (see Fig. 2).

Thus the hydrodynamic equations are narrowed down to the St. Venant equations and their derivatives. Accelerations are not of importance in overland or long river studies so these terms are omitted, and backwater effects are only of importance in some channel situations, so most modules are limited to kinematic type equations.

Flow is assumed uniform down the reach. That is, the water depth is constant down the reach. There may be local backup which does affect system storage however. Since inflow is thus spread over the full length of a reach each time step, the routing effect can be unrealistic unless the time step is sufficiently large. Methods of minimizing numerical routing (or using it to approximate time routing) have been investigated (Holden and Stephenson, 1988).

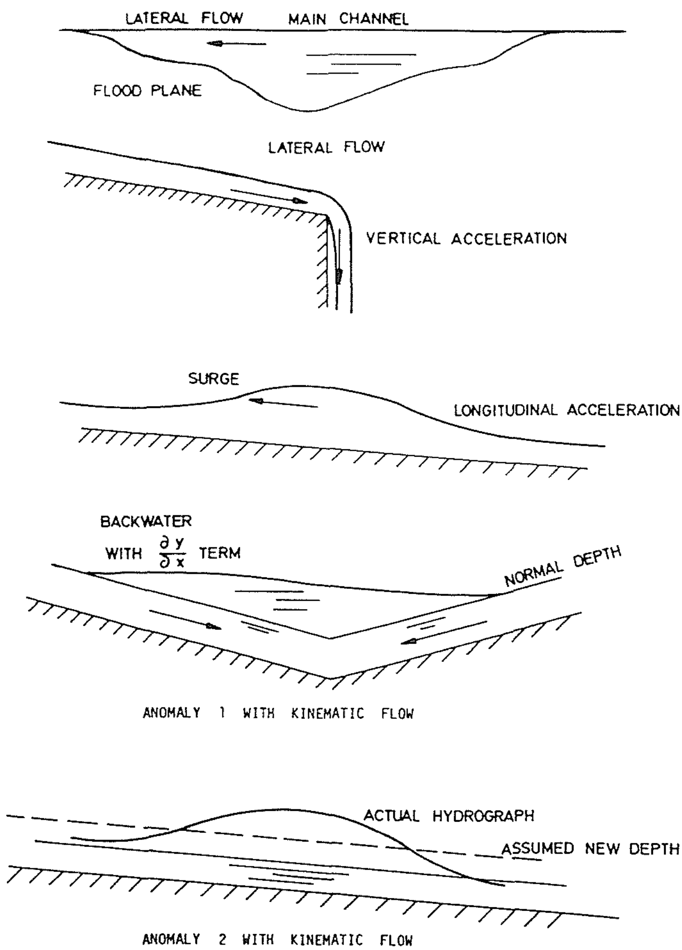

Fig. 2 Problems with specific numerical methods.

It should be noted the kinematic assumption of energy gradient parallel to conduit bed can cause complications at changes in slope. Depressions do not correctly store inflow, and separate storage modules are necessary.

CONTINUOUS SIMULATION

Groundwater flow capability with aquifer modules makes possible long term simulation of catchment yield. Groundwater contributions lag surface runoff by hours or even months. Recession limbs of stormwater hydrographs can be due to contributions from perched water tables or interflow. Longer term yields are from deeper aquifers.

Recharge of surface layers is however important from the point of view of antecedent moisture and permeability for forthcoming storms. The continuous simulation capability therefore improves estimation of surface storm runoff. Surface layer moisture is also important for estimating evaporation and losses.

The time scale of flow from deeper aquifers may be much longer than from the higher water tables, and a greater time step could be used once surface runoff is reduced.

The problem then arises as to future storm problems and their infiltration. However from the total yield point of view it is not critical if storm patterns are assumed.

ROUTING PROCESS

Kinematic waves are theoretically not subject to diffusion i.e. spreading and attenuation, as no dynamic effects are included in the equation. There may be changes in wave shape since dx/dt is a function of depth, but there can be no change in peak flow unless there is an inflow. The advantage of taking large distance increases with the kinematic method therefore results in a sacrifice in accuracy. Holden and Stephenson (1988) proposed a method for minimizing the numerical error and getting the best approximation to hydrodynamic diffusion.

The wave diffusion can be accounted for using the slightly more accurate equations, namely the diffusion equations, or the full dynamic equations. However in some cases wave diffusion can be reproduced numerically. From the mathematical point of view, numerical diffusion can be controlled or minimised. Explicit solution of the kinematic equations is often employed in preference to implicit solution as the friction equation is non-linear, and explicit schemes such as the backward centred, or semi explicit such as the 4-point scheme of Brakensiek (1967) are reasonably accurate and fast. Explicit schemes can be subject to numerical instability unless the time increment is small enough, i.e. $\Delta t < \Delta x/(dx/dt)$, (the Courant criterion) where $dx/dt = \alpha m y^{m-1}$. On the other hand the smaller Δt the greater the numerical diffusion as the numerical effect travels at a speed $\Delta x/\Delta t$. The optimum compromise is for $\Delta x/\Delta t = dx/dt$. This is not always possible in an equispaced grid as dx/dt varies. Ponce (1986) attempted to reproduce actual diffusion in kinematic equations by writing the finite difference equations for flow in a way similar to the Muskingum-Cunge routing equation.

Adopting a more practical approach the kinematic diffusion process can be explained as follows. The routing process which occurs with kinematic modelling is similar to reservoir routing where discharge depends only on the stage at the outlet. A unique stage

discharge relation is assumed i.e. no allowance is made for accelerations or water surface gradient. A compromise could be made by setting discharge a function of stage at more than one point e.g. average of upstream and downstream stages.

The resulting effect is similar to that employed in the Muskingum method and in addition allows for non-linearity in the stage-discharge relationship. It also has the advantage that the parameters in the equations are physically measurable and not empirical. To overcome the non-linear relationships the kinematic equations can be solved in two steps, namely the continuity equation to determine change in water depth, and discharge is obtained from stage using the selected discharge equation.

The discharge equation is not limited to a channel type equation such as that of Manning. Thus using a general discharge equation of the form

$$Q = Kh^m$$

if h is stage at discharge point and m = 5/3, *one has the Manning* equation, if m = 5/2 one has a triangular weir, m = 3/2 is a rectangular weir, m = 1/2 is an orifice and m = 1 is a deep rectangular channel. If h is the difference between upstream and downstream stages, then if m = 1/2 one has turbulent pipe flow, and if m = 1 one has laminar flow in a closed conduit or contained aquifer.

MANAGEMENT CAPABILITY

A drawcard of a model prepared on the above lines WITSKM (WITS STORM KINEMATIC MODULAR MANAGEMENT MODEL) is its versatility when it comes to redirecting flows and attenuating hydrographs. The facility of readily being able to redirect flows along different routes means channel storage or open versus closed conduit conveyance can be explored. The re-routing of flows along circuitous routes may increase channel storage. This in turn increases concentration time and could reduce design peak flows. New townships layouts could be varied until a suitable stormwater drainage pattern emerged.

The overflow facility also enables dual drainage to be used to maximum advantage. Excess flow could be led to shallow channels (or roadways) which will provide retardation or lead to channels which are only used in emergencies. the overflow level can readily be varied to permit difference risk storms to be accommodated in the minor (underground conduit) system.

The aquifer option is also of use in urban catchment management studies. Aquifers can be recharged by direct infiltration or with water led to them from less pervious areas. In either case the absorption of the aquifer is only limited by the depth-discharge characteristics and initial moisture conditions.

A useful module for hydrograph attenuation is the storage module. Reservoir surface area, dead storage and overspill crest level can be varied to achieve an optimum balance between maximum water depth and dam cost. The ability to vary the outlet discharge characteristic is however the most versatile facility of the storage module. By means of a general discharge equation of the form

$$Q = (WA)y^m$$

any form of outlet control can be used. For example an orifice is represented if m = 1/2 and WA = Ca $\sqrt{(2g)}$, where C is a discharge coefficient, a is the orifice cross-sectional area and g is gravity.

For detention attenuation which has a decreasing effect with

inflow, m should be high and for high detention at all depths m should be small. Again by trial, an optimum compromise between dam cost and cost of conveying away the discharge can be achieved.

MODULES

The versatility of the computer programme is enhanced by the possibility of fitting in various types of hydrological units or modules into a system. Catchments, aquifers, conduits and storage basins can be linked in any order. The various modules which can be built-in are as follows (Fig. 3).

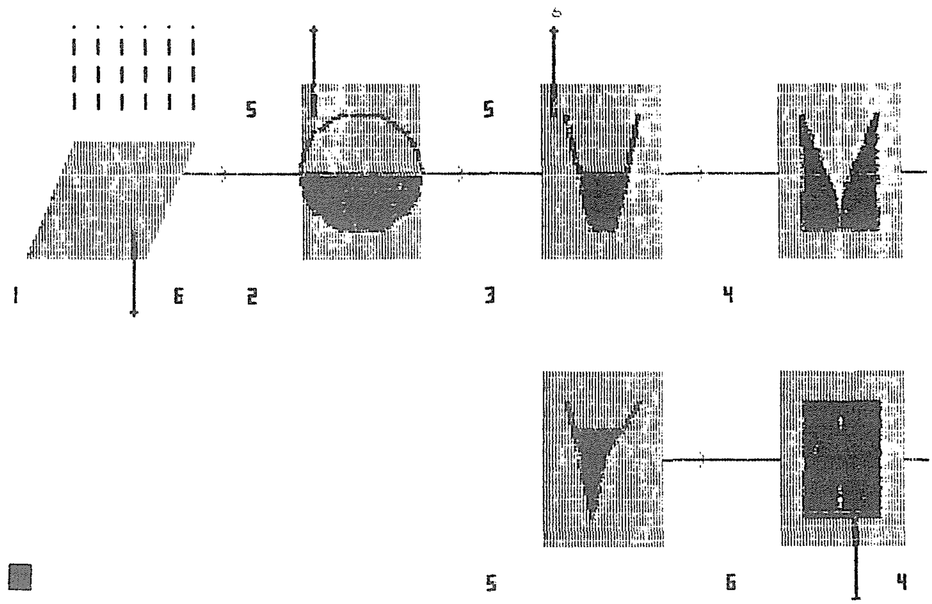

Fig. 3 Graphs output for connectivity check.

Catchments

A basic catchment is a rectangular shape sloping in one direction. The module reference number, its downstream module, initial water depth, length, width and discharge coefficient (ratio of discharge to depth to the power of 5/3) e.g. $\sqrt{(S/n)}$ where S is gradient and n is Manning roughness, are required as input data. In addition the surface permeability, suction at the ground wetting front, initial moisture content and aquifer module number are required. An infiltration process based on the soil physics model of Green and Ampt (1911) is assumed.

Catchments can be linked in cascades (in series) for example changing slopes or disconnected impervious surface, or in parallel, for instance if portion has directly connected impermeable cover.

Circular conduits (pipes)

Urbanized catchments are normally sewered with underground pipes, which run part full for most of the time. When they surcharge, the

excess flow continues down roads and may be directed to channels. Such a system ("major/minor" system) is common at high flows whether intentional or not and provides roads free of ponding for all but exceptional storms. The capability of modelling such systems is therefore important.

Data required for this type of module are module reference number, downstream module, initial depth, length, diameter, conveyance ($\sqrt{(S/n)}$), and overflow module number.

Trapezoidal channels

Open channels are the most common conduits, be they roadways, gutters, ditches or canals. Where the channel is a simple trapezoid, the data requirements are limited to module reference number, downstream module, initial flow depth, length, base width, conveyance, size slopes, maximum depth and overflow module.

Compound channels

Natural channels may be defined using an arbitrary number of co-ordinates across a section. The stream between any two neighbouring points is treated as an independent section so that velocity varies depending on flow depth and roughness. Flood planes are thus accommodated with slow moving storage on the banks and a more rapid stream between banks.

Data are module reference number, downstream module, initial depth, length, slope, points, co-ordinates and roughness of each section.

This facility can be used to calculate normal depth in compound channels. An impermeable catchment upstream with an area of 3600m x 100m is fed with Rmm of catchment rain (where R is normal flow in m^3/s) and after a period of time the depth in the downstream channel stabilizes at normal depth.

Storage basins

Where detention of retention is required, on- or off- channel storage may be of use.

Data required are module reference number, downstream module, initial water depth, length, width, conveyance α, discharge depth coefficient $m(Q = W\alpha y^m)$, side slope of basin, dead storage before discharge, and crest level of dam wall. By experimenting with the outlet e.g. crest or orifice spillway, a best design may be achieved.

Aquifers

Water may infiltrate to aquifers from catchments or be discharged directly into them from any conduit or overflow. The aquifer acts as a conduit albeit with a much slower flow rate. The aquifer will also have a maximum depth and may leak to a lower aquifer. Stacking or cascading of aquifers is possible. The kinematic equations are entirely adequate for this type of flow as dynamic effects are absent.

Data include aquifer reference number, downstream module number, initial flow depth, length, width, conveyance defined as kS where k is permeability and S is gradient, porosity, aquifer depth and underneath aquifer number.

OTHER FACILITIES

A frequent source of error in stormwater programs arise when downstream catchment number is changed or forgotten. A facility exists for displaying graphically on a PC colour screen the entire network once it is entered on the computer. Each module is drawn according to the type e.g. pipe, catchment, channel, and is connected upstream and downstream as indicated in the data. Overflow routes are also indicated. In general the model is designed for easy understanding and input and cross checking. It is especially useful for stormwater management studies. The groundwater modules enable continuous simulation to be performed, which is useful for establishing antecedant moisture conditions for storms, and dry weather flows (Fig. 4).

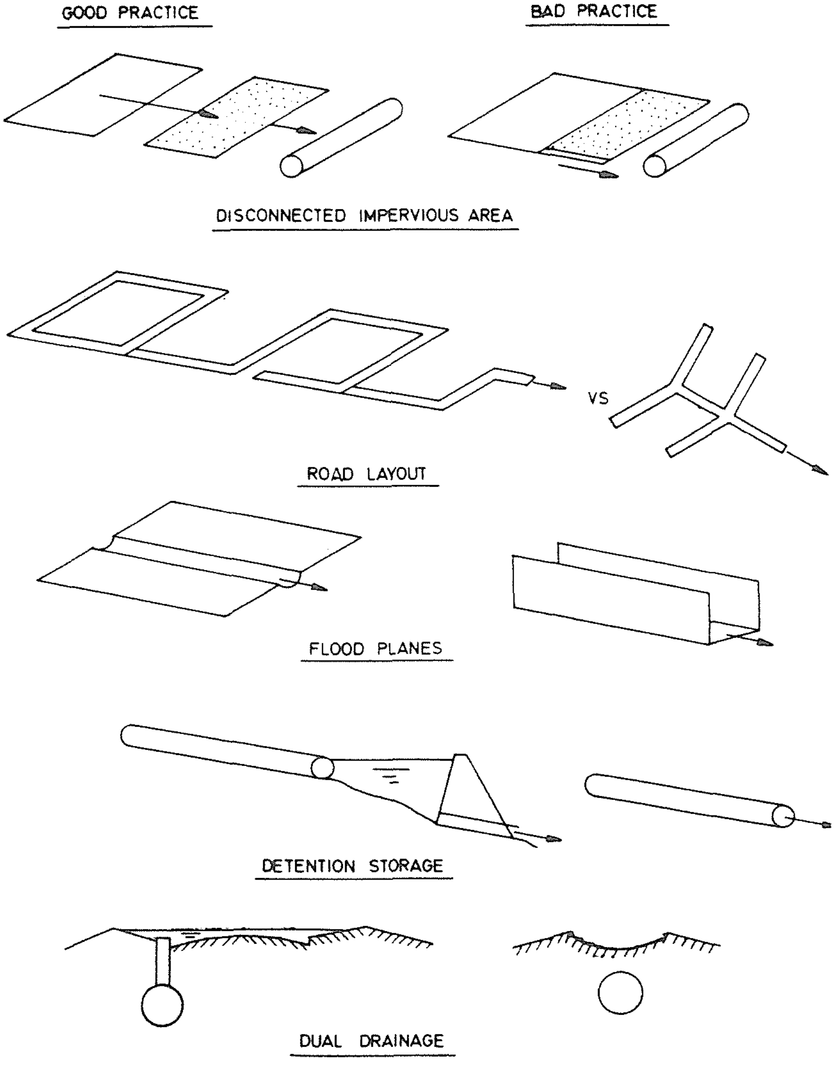

Fig. 4 Management methods investigated with model.

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